

Numerical study of the heat transfer in wound woven wire matrix of a Stirling regenerator



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ABSTRACT

Nusselt number correlation equations are numerically derived by characterizing the heat transfer phenomena through porous medium of both stacked and wound woven wire matrices of a Stirling engine regenerator over a specified range of Reynolds number, diameter and porosity. A finite volume method (FVM) based numerical approach is proposed and validated against well known experimentally obtained empirical correlations for a random stacking woven wire matrix, the most widely used due to fabrication issues, for Reynolds number up to 400. The results show that the numerically derived correlation equation corresponds well with the experimentally obtained correlations with less than 6% deviation with the exception of low Reynolds numbers. Once the numerical approach is validated, the study is further extended to characterize the heat transfer in a wound woven wire matrix model for a diameter range from 0.08 to 0.11 mm and a porosity range from 0.60 to 0.68 within the same Reynolds number range. Thus, the new correlation equations are numerically derived for different flow configurations of the Stirling engine regenerator. It is believed that the developed correlations can be applied with confidence as a cost effective solution to characterize and hence to optimize stacked and wound woven wire Stirling regenerator in the above specified ranges.

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1. Introduction

Stirling engine technology has been identified as an excellent candidate for energy cogeneration applications due to its elevate total efficiency (higher than 90%), the possibility to operate with any kind of temperature heat source (solar, combustible material, field waste, biomass, nuclear, etc.) and low noise and contamination levels [1–3]. The regenerator is considered by many researches as the key component to improve the efficiency of the next generation of Stirling engine systems [4–8]. In the Stirling-engine regenerators, the heat transfer and the pressure drop are the main phenomena associated to energy efficiency and have been studied by many researches [6,9–14,16]. For this reason, the characterization of these two phenomena through experimental, theoretical and numerical studies is crucial to maximize the thermal efficiency and incoming outsource energy in Stirling engine.

Research efforts [4,5,8–10,15] have shown that high fluid-to-matrix heat transfer together with low pressure drop can be obtained by using a matrix with the characteristics of: smooth heat

transfer surface, controlled flow acceleration rates, minimized flow separation and uniform passages flow distribution.

Currently, regenerators are usually made of stacked woven wire screen or random fibers. Thus, most of the research studies conducted for the thermal and fluid characterization in the Stirling regenerator have mainly focused on empirical characterization of these. The heat transfer between the matrix of the regenerator and the working gas has been studied from various points of view. Moreover, several experimental studies have been conducted in order to evaluate the heat transfer in different regenerator's matrices determining empirical correlation for Nusselt number Nu .

Tong and London [12] study the heat transfer and flow friction characteristics of woven wire screen and crossed rod in steady flow in a wide range of Reynolds number, Re . In the experiments each "screen element" is oriented 45° with its neighbor so as to simulate a "random stacking" in contrast to a "regular or aligned stacking" where all the wire elements, for instances, would be either parallel or right angles with each other.

Miyabe et al. [9] in addition to his theoretical work derives generalized experimental equations of flow friction factor and heat transfer coefficient for packed wire screens with variety of geometries. Tanaka et al. [6] investigates the flow and heat transfer characteristics of the regenerator materials in an oscillating flow for

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Nomenclature

A	heat transfer area (m ²)	R	gas-law constant (J/kg K)
A_{wr}	regenerator matrix wetted area (m ²)	Re	Reynolds number (–)
c_1, c_2, c_3	Nusselt correlation constants (–)	Sh	volumetric rate of heat generation (W/m ³)
c_p	heat capacity at constant pressure (J/kg K)	s	cell size (m)
c_v	heat capacity at constant volume (J/kg K)	s	Pitch of the mesh (–)
d_h	regenerator matrix hydraulic diameter (m)	T	temperature (K)
d_w	wire diameter (m)	T_g	working gas temperature (K)
E	total energy (J)	T_r	regenerator matrix temperature (K)
h	heat transfer coefficient (W/m ² K)	t	time (s)
h_s	sensible enthalpy (J/kg)	u	velocity magnitude in x direction (m/s)
$\bar{J}_j$	diffusion flux of species (kg/m ² s)	u_{max}	matrix velocity (m/s)
k	thermal conductivity (W/m K)	V_t	total volume of regenerator matrix (m ³)
k_{eff}	effective conductivity (W/m K)	$\vec{v}$	overall velocity vector (m/s)
k_g	working gas thermal conductivity (W/m K)	Y_j	mass fraction of species (–)
k_t	turbulent thermal conductivity (W/m K)	μ	fluid dynamic viscosity (kg/m s)
$\dot{m}$	mass flow rate (kg/s)	ρ	fluid density (kg/m ³)
Nu	Nusselt number (–)	Π_v	regenerator matrix volumetric porosity (–)
p	pressure (Pa)	φ	regenerator matrix specific heat transfer area (1/m)
Pe	Peclet number (–)	ϕ	regenerator matrix shape factor (1/m)
Q	heat transfer (W)	τ	non-dimensional time (–)
q	heat flux (W/m ²)	$\bar{\tau}$	stress tensor (Pa)

wire net and sponge metal. Gedeon and Wood [10] derive generic correlations for friction factor, Nusselt number, enhanced axial conduction ratio and overall heat flux ratio based on the test samples of a number of wire mesh (random stacking) and metal felt, with a range of porosities.

Thomas and Bolleber [17] compare different and often used correlations for heat transfer of Stirling engine regenerators. Each author formulates a different definition for Reynolds and Nusselt numbers as well as heat transfer area. All those authors use samples of wire screen or random fiber matrices for their investigations.

Generally, the Nusselt number is a function of Reynolds and Prandtl number (Peclet number) [10]. However, when dealing with the heat transfer in the regenerator of a Stirling machine, the Prandtl number is insignificant, since it can always be approximated as 0.7 for the gases used as working fluids in Stirling machines. The impact of Re is given by the following general correlation [17]:

$$Nu = c_1 + c_2 Re^{c_3} \quad (1)$$

In Eq. (1) the coefficient are constants determined by the experimental data. Thomas and Bolleber [17] observe that the Nusselt number is not only a function of Reynolds number. The majority of experimental data reveal the additional impact of the porosity on Nusselt number. Thus the effect of the porosity must be attributed to the specific heat transfer area. The impact of the property data on the working fluid, given by the Prandtl number, is also negligible.

Apart from the analytical studies, there are some numerical analyses of the heat transfer and pressure drop through wire screen matrix using different numerical discretization techniques. The finite volume method (FVM) appears to be promising as numerical investigation tool indicated by Rühlich and Quack [5], Gedeon and Wood [10], Ibrahim et al. [7], Tew [18], Cheadle et al. [19], Tao et al. [20] and others. These numerical studies suggest that the fluid flow and thermal simulations are highly required to understand the flow of interest and hence to characterize fluid flow friction behavior for such systems of regenerator applications. The work of Cheadle et al. [19] outlines the development of a design tool that is capable of deriving Nusselt number and friction factor correlations based on computational fluid

dynamic (CFD) analysis of a 2-D unit-cell model that considers the microscopic interactions between the fluid and solid.

Kolodziej et al. [13] indicate that despite the fact stacked wire screen are used for years in different applications that involves heat recuperation or regenerators, their transport and friction phenomena are still not described well enough. The number of studies dealing with the gauze flow resistance and heat transfer is rather limited. Moreover, there is a considerable lack of more general models that could be able to predict transport properties of any wire gauze, which have not been experimentally described before.

One important issue in the progress to improvements Stirling models is the geometrical shape of the matrix in the regenerator and most regenerator models don't assume a precise geometrical shape for the elements of the regenerator [21]. Dydson et al. [21] indicate that clearly, the shape of the regenerator has an important impact on the overall Stirling system design.

As summarized above, the majority of experimental studies and correlations are generally conducted for stacked woven wire screen regenerator matrices as they are the most widely used ones. However, this kind of regenerator tends to be the one of the most expensive components of the Stirling engines, which nowadays limits the use of this technology for micro-cogeneration application in domestic environments. For this reason, the use of wound woven wire matrix regenerators could be a more cost effective alternative solution that would overcome such limitations [16]. Therefore, heat transfer and flow friction characteristics of these matrices are of interest for Stirling cycle applications. Even though, very few research works have been carried out for this type of regenerator, no specific heat transfer correlations are known to exist in literature. Thus, there is still a very high necessity of characterize heat transfer in this type of regenerator.

Consequently, the objective of this study is to numerically develop a heat transfer correlation for wound woven matrix regenerator. With this respect, numerical 3-D detailed models for a stacked woven wire matrix are initially developed to obtain heat transfer correlations for different configurations and the results are compared with well-known experimentally obtained correlations in order to validate the proposed models over a specified range of Reynolds number. Later, the numerical study is extended

to obtain heat transfer correlation equation for wound woven wire matrices. The good correspondence of the stacked woven wire matrix configuration with experimental data suggests that the derived correlations can be used with confidence to characterize and hence to optimize wound woven wire matrix Stirling regenerator. However, it is expected that the developed correlations will be experimentally validated for future applications and used to limit the try and error cost in Stirling design. It should be noticed that a similar study dealing with the development of numerical correlation for the flow friction factor through a wound woven matrix regenerator, has been recently published by the authors [16].

2. Computational Principles

2.1. Numerical methodology

The numerical methodology adopted in the previous work of the authors [16] for the numerical resolution of pressure drop characteristics of Stirling flow under isothermal flow condition is extended here to investigate the heat transfer phenomena by solving additional governing integral equation for the conservation of energy in de-coupled (segregated) manner.

In this study, the fluid is considered to be viscous, unsteady, incompressible and Newtonian with constant fluid flow properties, and three-dimensional (3-D) with assumption of laminar flow behavior at very low Reynolds number range and of turbulent flow behavior at high Reynolds number. As authors demonstrate in previous work [16], when the Reynolds number exceeds a certain value depending on the configuration of the wire matrix used, the local instabilities due to emergence of turbulence leads to numerical convergence problem and the simulations are conducted in turbulent manner.

In this study due to the small range of temperature used in each case, all fluid properties (including density, viscosity, specific heat, and conductivity) are assumed constant. The present flow is mathematically governed by continuity, momentum and energy equation. The governing equations are discretized and solved sequentially using a finite volume method (FVM) based numerical flow solver [22] with a second order upwind scheme for the discretization of the continuity, momentum and energy equations for the laminar flow solutions. The convergence criterion for all the velocity components and for the continuity is set to 10^{-6} , whereas it is set to 10^{-8} for the energy for all simulations. The non-dimensional time step, $\tau = u_{\max}/s$ is expressed as the product of the maximum velocity component at the inflow boundary and time elapsed divided by the volume cell size. The non-dimensional time step values are chosen as 0.01 following an initial sensitivity analysis performed for the variation of Nusselt number with respect to different non-dimensional time step size ranging from 0.001 to 0.01 for different Re number of 64 and 355. This test shows that there is no significant influence of choice of non-dimensional time step size between 0.01 and 0.001 on the results of Nusselt number obtained for the investigated Re number.

2.2. Computational domain and boundary conditions

Fig. 1 illustrates the region of flow of interest (geometry set-up) in which the woven wire matrix and the flow through woven wire matrix geometry is extensively analyzed as a representation of a differential part of a Stirling regenerator arrangement. As Cheadle et al. [19] mention the modeling of typical regenerator geometries would require detailed 3-D models with prohibitively long solutions times. For this reason, in order to capture the heat and momentum interactions at the microscopic level, a small representative portion of the regenerator is modeled. The inlet and outlet

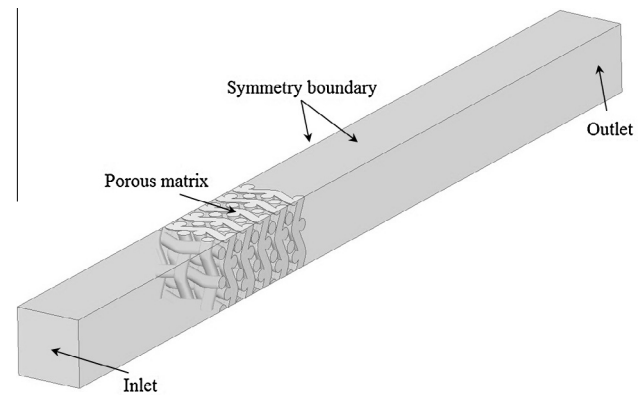


Fig. 1. Global computational domain for stacked woven wire matrix.

flow areas are set to approximately 0.5 mm^2 and woven wire matrix length is approximately 1.5 mm.

The Reynolds number based on hydraulic diameter is varied from 4 to 400. In some simulations the computational domain is further extended in the downstream direction (in the nominal direction of the outlet flow) in order to avoid reverse flow conditions at the outflow boundary.

In the geometrical model to simulate the random stacking of the different sheets, two different misaligned configurations, parallel and cross, for stacked woven wire matrix are generated and studied. In the wound woven wire matrix just the misaligned parallel configuration is generated and studied because in a winding process the cross case is more difficult to obtain. All the configurations are generated based on two woven wire mesh, $80 \mu\text{m}$ and $110 \mu\text{m}$ as described in Table 2. Furthermore, for each woven wire mesh small changes in the volumetric porosity ranges, Π_v , are realized. The range of porosity evaluates is from 0.60 to 0.68. Fig. 2a and b show the configurations for parallel and cross local matrix for stacked woven models, respectively.

Miyabe et al. [9] indicates that the empirical equation derived for Nusselt is expressed in a generalized form, and it is recommended that the matrix be made so that all screens are closely stacked. If each screen is not stacked perfectly, or when any gap exists between the screens, the friction coefficient and Nusselt number will deviate from the actual value to some extent.

In Fig. 3 are shown the matrix surface mesh for a stacked and wound woven wire matrix and a two-dimension section in the flow direction for fluid.

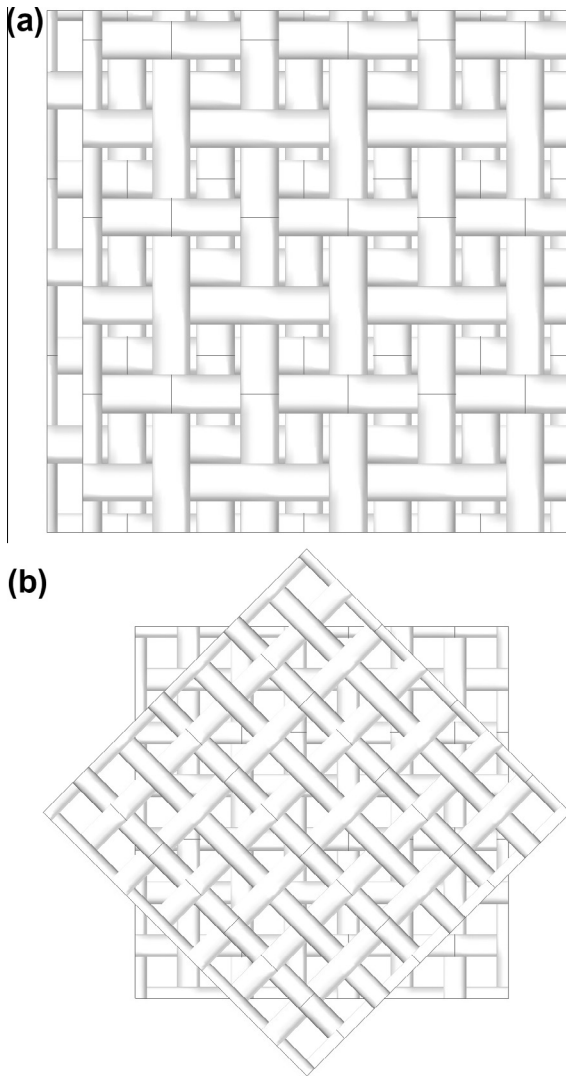
The computational domain is constructed of non-uniformly distributed different hybrid mesh systems containing over 2.5 million tetrahedral and/or hexahedral volume cells for the final mesh system. The tetrahedral cells are used in the wire matrix and air volume inside the matrix with very fine mesh resolution in the close vicinity of the wire surfaces to resolve sharply varying velocity and pressure gradients there. The effect of the mesh resolution on the flow has been previously assessed with the authors [16] for three different mesh systems containing non-uniformly distributed hybrid grid cells in a quarter of the computational domain. It is demonstrated that there is no major difference among the computed values and the mesh system of over 2.5 million hybrid volume cells, in the current study the number of cell is multiplying by four. Thus, the final mesh system could be considered to be fine enough to study the effects of Reynolds number on the heat transfer characterization.

For all woven wire matrix configurations, all model simulations are carried out by considering the following boundary conditions:

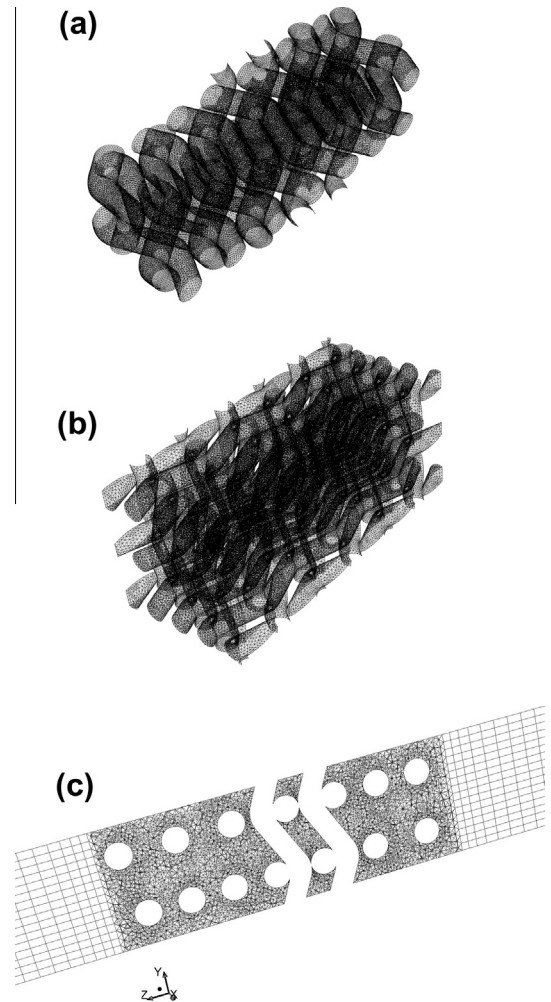
Table 1

Gedeon/Wood [10] and Tanaka et al. [6] tested regenerator matrix parameters.

Study	Wire mesh geometry				Regenerator matrix geometry		
	Wire/inch	d_w (μm)	Opening (μm)	Porosity (%)	Π_v (%)	ϕ (1/ μm)	d_h (μm)
Gedeon/Wood [10]	200	53.3	74	67.0	62.3 (−4.7)	0.028	88
Gedeon/Wood [10]	100	55.9	198	82.7	78.1 (−4.6)	0.016	199
Gedeon/Wood [10]	80	94	224	76.7	71.0 (−5.7)	0.012	230
Tanaka et al. [6]	50	230	278	64.4	64.5 (+0.1)	0.006	418
Tanaka et al. [6]	100	100	154	69.1	71.1 (+2.0)	0.012	246
Tanaka et al. [6]	150	60	109	72.2	75.4 (+3.2)	0.016	184
Tanaka et al. [6]	200	50	77	69.1	72.9 (+3.8)	0.022	135

**Fig. 2.** 2D flow perpendicular plane layouts: (a) parallel stacked misaligned and (b) cross stacked misaligned configurations.

1. **Inflow boundary:** Velocity inlet boundary conditions at constant temperature are used to define the fluid uniform velocity profile.
2. **Outflow boundary:** Pressure outlet boundary conditions are assigned to define the static (gauge) pressure by eliminating reverse flow problem.
3. **Side boundary:** Free-slip symmetry flow boundary conditions at the four side boundaries of the computational domain are imposed. The normal velocity components and the normal gradients of all velocity components are assumed to have a zero value.

**Fig. 3.** (a) 3D view of the surface mesh for a stacked woven wire matrix; (b) 3D view of the surface mesh for a wound woven wire matrix and (c) 2D plane view of stacked woven wire flow mesh.

4. **Interior wall boundaries:** No-slip wall boundary conditions together with the enhanced wall functions are assigned to interior wall boundaries between wires and fluid for turbulent simulation cases. Moreover, any thermal condition is assigned to the wall between the fluid and the solid matrix, and the two sides of the wall are coupled.

2.3. Heat transfer model

The energy equation form solves in ANSYS FLUENT [22] is the following:

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot (\vec{v}(\rho E + p)) = \nabla \cdot \left(k_{eff} \nabla T - \sum_j h_j \vec{J}_j + (\vec{\tau}_{eff} \cdot \vec{v}) \right) + S_h \quad (2)$$

where k_{eff} is the effective conductivity ($k + k_t$), where k_t is the turbulence thermal conductivity, defined according to the turbulence model being used, and $\vec{J}_j$ is the diffusion flux of species j . The first three terms on the right-hand side of Eq. (2) represent energy transfer due to conduction, species diffusion, and viscous dissipation respectively. S_h includes the heat of chemical reaction, and any other volumetric heat sources defined.

In Eq. (2)

$$E = h_s - \frac{p}{\rho} + \frac{v^2}{2} \quad (3)$$

where sensible enthalpy h_s is defined for incompressible flow as

$$h_s = \sum_j Y_j h_j + \frac{p}{\rho} \quad (4)$$

for ideal gas the last term of Eq. (4) is eliminated. In Eq. (4), Y_j is the mass fraction of species j and

$$h_j = \int_{T_{ref}}^T c_{p,j} dT \quad (5)$$

In one-dimensional the gas energy Eq. (2) is written as:

$$\frac{\partial}{\partial t}(\rho E) + \frac{\partial}{\partial x} \cdot (u(\rho E + p) + q) - Q = 0 \quad (6)$$

Solid matrix to gas heat transfer Q can be expressed in terms of a heat transfer coefficient h as follow:

$$Q = hA(T_r - T_g) \quad (7)$$

Ignoring the kinetic energy term ($u^2/2$) in Eq. (6), and expressing $\rho E = (c_v/R)p + p = c_p \rho T$, the alternative form of the energy equation is:

$$(c_{v,g}/R) \frac{\partial p}{\partial t} + \frac{\partial}{\partial x} \cdot (c_{p,g} \dot{m} T_g + q) - hA(T_r - T_g) = 0 \quad (8)$$

Eq. (8) is transformed into Eq. (9) assuming that the first term of the Eq. (8) is negligible, the mass flow is uniform in the matrix, the matrix temperature is linear and the apparent conductivity is not a function of x . By combining the last two assumptions the $A_{wr} \tau_m$ becomes as $\frac{\partial q}{\partial x} = k_a \frac{\partial^2 T}{\partial x^2} \approx 0$.

$$\dot{m} c_{p,g} \frac{\partial T_g}{\partial x} = hA(T_r - T_g) \quad (9)$$

Eq. (9) is easily solved to given the heat transfer coefficient based on numerical modeling results between two planes Δx as follows:

$$h = \dot{m} c_{p,g} \Delta T_g / A_{wr} \Delta T_{m_{log}} \quad (10)$$

where $\dot{m}$ is the mass flow of the working gas, $c_{p,g}$ is the gas specific heat at constant pressure, ΔT_g is the different in gas temperature between the entrance and exit plane in the model, is the regenerator wetted area and $\Delta T_{m_{log}}$ is a logarithmic average of the temperature difference between the regenerator matrix surface and working gas.

Eq. (10) shows that in regenerator matrices experimental analysis the specific heat transfer area is necessary to calculate the heat transfer coefficient. In the majority of experimental studies [6,10] the heat transfer area of woven wire screens is expressed as $\varphi = \pi/sV_t$ where s is the pitch of the mesh and V_t is the total volume of the regenerator [17]. Miyabe et al. [9] suggests reducing the gross heat transfer area, given by the total surface of the wires in the matrix, by the contact areas between each two wires. Thomas and Bolleber [17] prove that the reduction of the total surface area

of the matrix by the contact areas between the wires is necessary in order to correlate experimental heat transfer data of Stirling engine regenerators. Moreover, the results presented by Kolodziej et al. [13] indicate that the number of wire sheet stacked in the test did not influence the heat transfer intensity because in their experiments the sheets were separated by thin gaps to avoid their contact.

In the present study the wetted regenerator area A_{wr} is measured in the detailed geometry (CFD or CAD program) where only the contact between solid matrix and fluid is considered. For stacked woven wire mesh the contact volumetric porosity is decreased in a similar range that Gedeon and Wood [10] as can be compared between Tables 1 and 2. The computational domain is initially at a uniform temperature different from inflow temperature.

3. Results and discussion

3.1. Numerical validation: heat transfer correlation for stacked woven wire matrix

In this section, the numerical simulations are performed using a proposed FVM method based numerical solution for the stacked woven wire matrix and a Nusselt number correlation equation is derived from the results. The derived correlation is validated against empirical results provided by Tanaka et al. [6] and Gedeon and Wood [10], over a range of wire diameter, Re number and volumetric porosity summarize in Table 1.

Tanaka et al. [6] investigates the flow and heat transfer characteristics of regenerator materials in an oscillating flow for conventional stacked woven wire matrix, sponge metal (felt) and sintered metal. Tanaka et al. [6] obtains the heat transfer area by multiplying the specific area of the mesh by the regenerator total volume. Tanaka et al. [6] suggests that the heat transfer coefficient in the oscillating flow may be higher than that in unidirectional flow.

Gedeon and Wood [10] present correlating expressions in terms of Reynolds or Peclet number for friction factors, Nusselt numbers, enhanced axial conduction ratios and overall heat flux ratios in stacked woven wire matrices and metal felt test regenerator samples. One of the main conclusions of the Gedeon and Wood [10] investigation is that under the range of conditions tested, which were intended to be representative of most Stirling applications, they found no essential differences compared to steady flow. In other words, instantaneous local Reynolds number or Peclet number appear to characterize the flow quite adequately.

As can be observed there is not a clear consensus about the effect of the oscillating flow conditions in the Stirling regenerators. On one hand, Tanaka et al. [6] suggests that it could enhance the heat transfer and in the other hand, Gedeon and Wood [10] conclude that there are not significant different with steady conditions in the Stirling regenerator working range. In the previous authors work [16] the numerical results show good agreement with the experimental results obtained under oscillating flow conditions, despite the study is conducted under not oscillating flow conditions. Therefore, those experimental investigations are considered for the validation of the numerical model presented for the study of stacked woven wire matrix regenerator.

In both studies the maximum Reynolds number is calculated based on hydraulic diameter, d_h instead of wire diameter. The hydraulic diameter is defined by Tanaka et al. [6] as:

$$d_h = 4\Pi_v/\phi(1 - \Pi_v) \quad (11)$$

where Π_v is the volumetric porosity and ϕ is the shape factor defined as the ratio of the mesh surface area to the mesh volume.

The hydraulic diameter is defined by Gedeon and Wood [10] as:

Table 2

Present study modeled regenerator matrix parameters.

Study	Wire mesh geometry				Regenerator matrix geometry		
	Wire/inch	d_w (μm)	Opening (μm)	Porosity (%)	Π_v (%)	ϕ (1/ μm)	d_h (μm)
Present Study	113	80	144	72.0	66 (–6)	0.017	155
Present Study	113	80	144	72.0	68 (–4)	0.016	170
Present Study	100	110	144	66.0	60 (–6)	0.015	165
Present Study	100	110	144	66.0	63 (–3)	0.013	187

$$d_h = d_w \Pi_v / (1 - \Pi_v) \quad (12)$$

The difference between these two definitions (Eqs. (11) and (12)) of diameter hydraulic is not significant. In the present study the hydraulic diameter is determined by Eq. (12).

The specific heat transfer area in a woven wire mesh, ϕ , is generally defined as:

$$\phi = 4/d_w(1 - \Pi_v) \quad (13)$$

Therefore, Reynolds number can be defined as:

$$Re = \rho u_{max} d_h / \mu \quad (14)$$

The maximum flow velocity u_{max} is obtained by dividing the frontal maximum velocity by porosity. The Nusselt number is then defined as follows:

$$Nu = h d_h / k_g \quad (15)$$

In the present numerical study the heat transfer coefficient is calculated from the numerical result using Eq. (10).

Although the purpose of the present study is to estimate the heat transfer in a wound woven wire matrix, since there is no experimental data available for this case, the first step is to validate the computational model for a stacked woven wire matrix in comparison with the experimentally obtained empirical correlations proposed by cited researchers above. The validation is made using two different wire diameters and two configurations of matrices in which, the first configuration is a stacked woven wire screens parallel misaligned and the second matrix configuration is oriented 45° with its neighbor so as to simulate a “random stacking”. Furthermore, the stacking volumetric porosity has two levels for the same woven wire mesh in order to cover any possible stacking process variation. In Table 2 the parametric study range for stacked woven wire matrices is summarized.

Tanaka et al. [6] proposes the following empirical relationship for Nusselt number in a range of $10 < Re < 150$:

$$Nu = 0.33 Re^{0.67} \quad (16)$$

Gedeon and Wood [10] based on combining data sets proposes the following master correlation for woven wire matrix in terms of Peclet number ($RePr$):

$$Nu = (1 + 0.99 Pe^{0.66}) \Pi_v^{1.79} \quad (17)$$

Gedeon and Wood [10] justify the constant 1 in the Nusselt number expression (Eq. (17)) because Nu tends to some constant value for $Pe \approx 0$ as occurs in fully developed internal laminar flow. Gedeon and Wood [10] claim that a value of $Nu_0 \approx 1$ seems reasonable in light of the published limiting value of 0.43 for flow normal to a single cylinder. Eq. (17) becomes Eq. (18) for $Pr \approx 0.73$ and $\Pi_v \approx 0.69$ (average volumetric porosity in the present study):

$$Nu = 0.51 + 0.40 Re^{0.66} \quad (18)$$

The relative accuracy of the results of Gedeon and Wood [10] for heat transfer correlations is more dependent on Reynolds number. Thus the worst relative error is about 10% at peak Reynolds number on the order of 1000 and it is about 50% for peak Reynolds numbers below about 5.

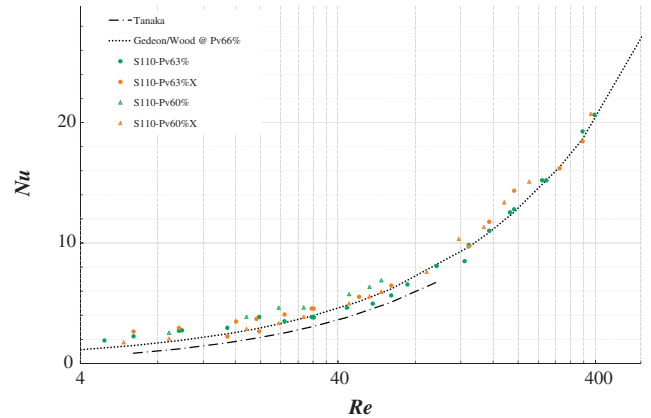


Fig. 4. Stacked woven wire matrices for 110 μm wire diameter: Nusselt number versus Reynolds number.

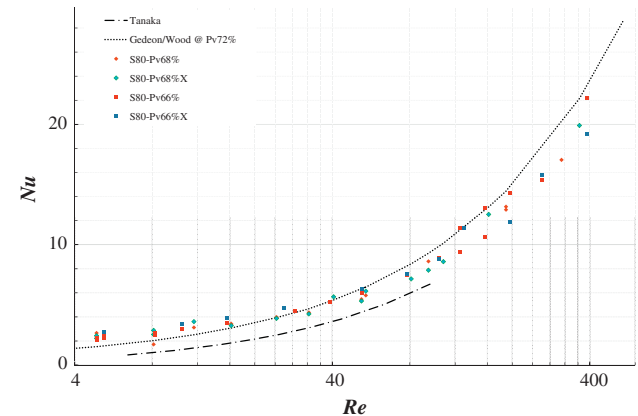


Fig. 5. Stacked woven wire matrices for 80 μm wire diameter: Nusselt number versus Reynolds number.

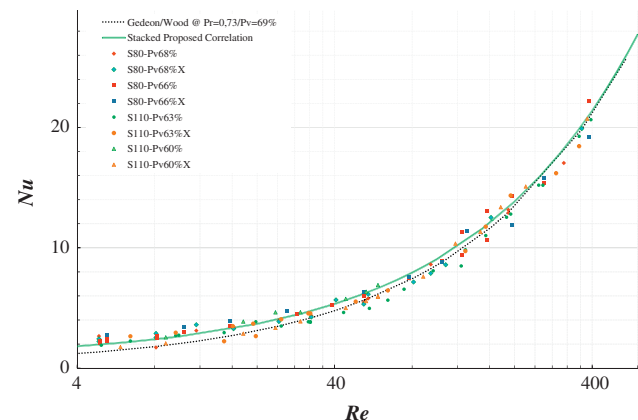


Fig. 6. Nusselt number correlation comparison for Stacked woven wire matrices.

Table 1 summarizes the geometrical characteristics of the woven wire mesh and the samples tested for different authors. It is important highlighted that in the regenerator samples used by Gedeon and Wood [10] for obtained empirical correlations the Π_v is approximated 5% lower than the single mesh Π_v . However, in the samples used by Tanaka et al. [6] the Π_v is approximated 3% higher, this could means that there is not contact between different layers. In the present study the models are similar to the Gedeon and Wood [10] as is shown in Table 2.

Eight different configurations of stacked woven wire matrices are numerically studied, four of them are parallel configuration (Fig. 2a) and the others are cross configurations (Fig. 2b). Based on heat transfer results the Nusselt number is calculated for a Reynolds number range from 4 to 400. By fitting these results to the three coefficient equation form (Eq. (1)), Nusselt number correlation equation is obtained.

Fig. 4 shows the numerical results obtained for stacked woven wire matrices, 110 μm wire diameter, together with the Nusselt number evolution determined due to Tanaka et al. [6] and Gedeon and Wood [10] for a volumetric porosity of 0.66. The volumetric porosity chosen corresponds to the volumetric porosity of a single 110 μm wire diameter screen. Fig. 5 on the other hand shows the results for the 80 μm wire diameter together with the distribution of the Nusselt number for a volumetric porosity of 0.72 due to Gedeon and Wood [10].

It is observed from Figs. 4 and 5 that no noticeable difference is reproduced for the Nusselt number obtained for parallel or cross stacked woven wire matrices configuration or even in the range of volumetric porosity studied. Nevertheless, it is necessary to emphasize here that the variation in volumetric porosity is not significant and the same behavior is also observed for the woven wire mesh geometry. Therefore, the matrix heat transfer area (specific heat transfer area) decreases with an increase in volumetric porosity. In the majority of the samples tested by Gedeon and Wood [10] the volumetric porosity increases with the specific heat transfer area (Table 1).

Regarding the correspondence of the present numerical results with the Nusselt number derived from empirical correlations, it is obvious from Figs. 4 and 5 that the numerical results are not good correspondence with correlation proposed by Tanaka et al. [6]. However, the numerical results fit well with the correlation proposed by Gedeon and Wood [10].

Eq. (19) shows the derived numerical correlation for the stacking woven wire matrix which fit the numerical results for the Nusselt number.

$$Nu = 1.14 + 0.39Re^{0.66} \quad (19)$$

Fig. 6 demonstrates that Nusselt number correlation equation proposed in the present study for stacked woven wire matrices (Eq. (19)) shows a good agreement with the numerical results obtained

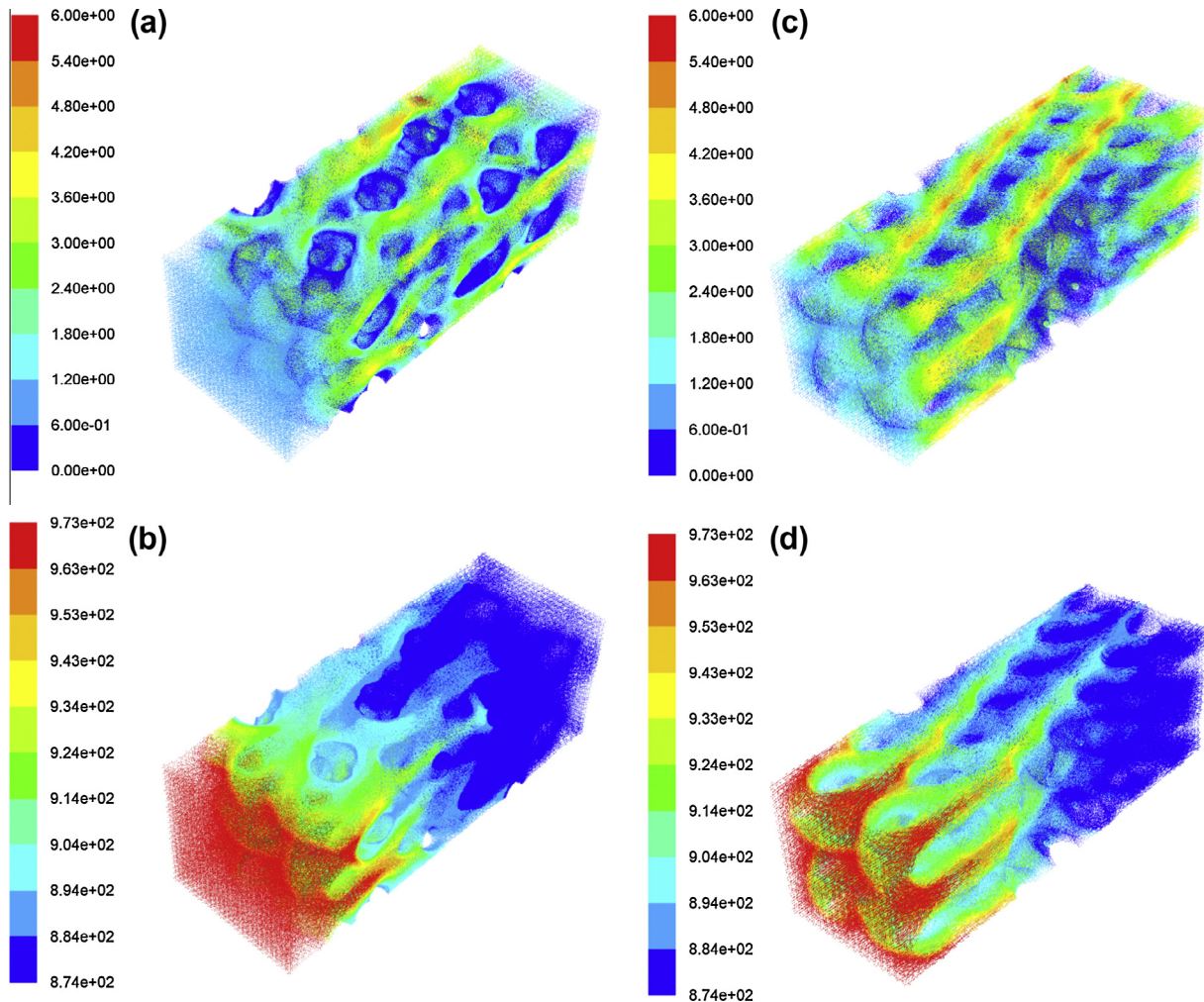


Fig. 7. Stacked woven wire matrices results for $Re \approx 60$ ($u_{in} = 1$ m/s) at 0.02 s: (a) Velocity vector through 80 μm matrix; (b) Velocity vector colored by temperature through 80 μm matrix; (c) Velocity vector through 110 μm and (d) Velocity vector colored by temperature contour through 110 μm matrix.

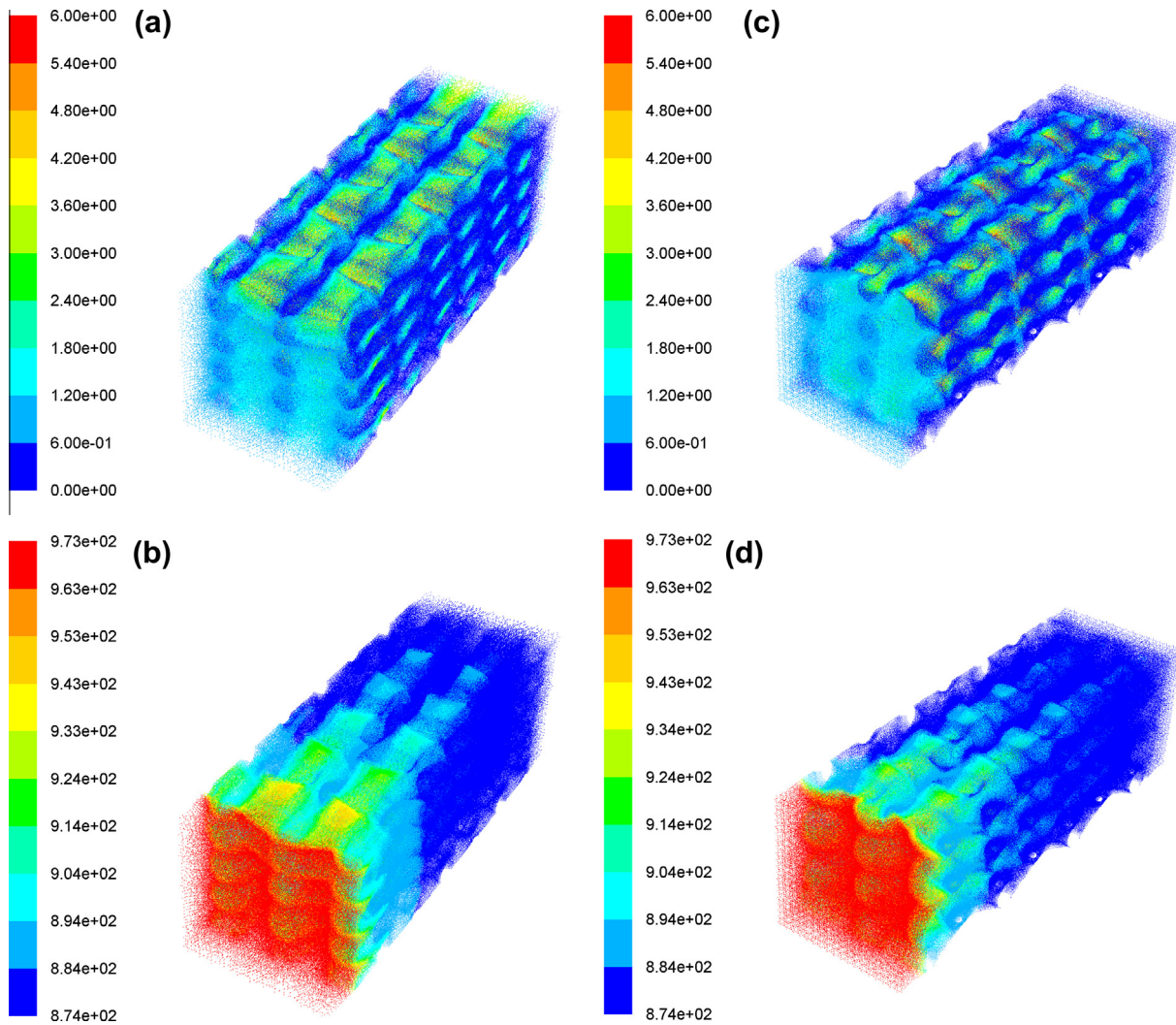


Fig. 8. Wound woven wire matrices results for $Re \approx 60$ ($u_{in} = 1$ m/s) at 0.02 s: (a) Velocity vector through 80 μm matrix; (b) Velocity vector colored by temperature through 80 μm matrix; (c) Velocity vector through 110 μm and (d) Velocity vector colored by temperature contour through 110 μm matrix.

for the Nusselt number as a function of Reynolds number. Moreover, for Nusselt number, with the exception of the Reynolds number range below 40, the agreement is within 10% with Gedeon and Wood [10] empirical correlations (Eq. (17)). However, for $Re < 40$ the present numerical results deviate significantly from the Gedeon and Wood [10] empirical correlations. Gedeon and Wood [10] conclude that the experimental correlation proposed is not appropriate for low Reynolds number range. In the other hand, the agreement with Tanaka et al. [6] proposed correlation is not good.

The effect of the volumetric porosity on the Nusselt number is not observed and this is probably due to the fact that the specific heat transfer area in the configuration studied (Table 2) does not present a significant range of variation. Moreover, it is expected that the heat transfer behavior be improved with the increase of specific heat transfer area. The effect of the volumetric porosity and specific heat transfer area on the regenerator heat transfer will be studied in future investigation.

The qualitative results for velocity and temperature fields the stacked woven wire matrices are illustrated in Fig. 7a–d at Re number of 60 for two different wire diameters of 80 μm and 110 μm . No significant differences are observed at different wire diameters except slightly higher maximum local velocity distributions obtained from the higher wire diameter of 110 μm for the stacked woven wire matrices as illustrated in Fig. 7a and c. The velocity

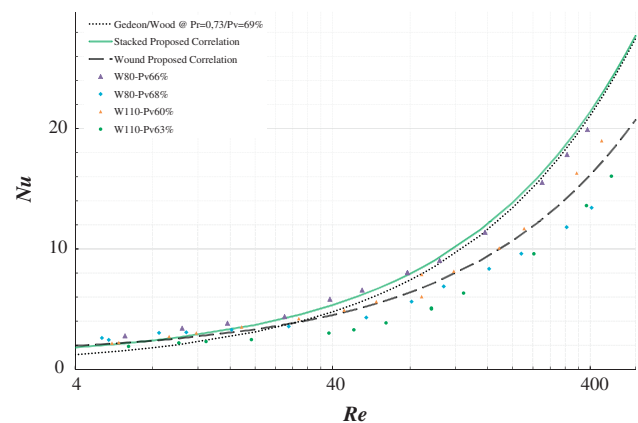


Fig. 9. Nusselt number correlation comparison for Wound woven wire matrices.

contours in the wire matrix domain also signifies the importance of local increase of velocity magnitudes as an indication of shear gradients leading to the higher shear stress and hence friction pressure drops for each case. The higher local temperature values obtained in the flow entry region for each wire diameter case can

Table 3

Tanaka et al. [6] and Gedeon and Wood [10] experimental range for stacked woven wire matrix and experimentally obtained empirical correlations for Nusselt number, and present study numerical correlations for Nusselt number.

	Wire diameter (μm)	Porosity (%)	Re range	Correlation
Tanaka et al. [6]	50–230	64–73	10–150	$Nu = 0.33Re^{0.67}$
Gedeon/Wood [10]	53.3–94	62–78	1.04–3400	$Nu = 0.51 + 0.40Re^{0.66}$
Stacked present study	80–110	60–68	4–400	$Nu = 1.14 + 0.39Re^{0.66}$
Wound present study	80–110	60–68	4–400	$Nu = 1.54 + 0.29Re^{0.66}$

^a The correlation for Nusselt number is for a $Pr \approx 0.73$ and $\Pi_v \approx 0.69$.

be considered to be main source of the heat energy to be transferred to the entire flow domain as the flow progresses.

3.2. Heat Transfer correlation for wound woven wire matrix

Having been validated for the stacked woven wire matrices, the present numerical approach is extended to investigate the heat transfer characteristics and the corresponding heat transfer coefficients for wound wire matrix configurations. The configurations studied are the same studied for parallel misaligned stacked woven wire matrices (Table 2).

Fig. 8a–d also signifies the local variation of velocity and temperature field values for the wound woven wire matrices at Re number of 60 for two different wire diameters of 80 μm and 110 μm . Similar space-wise evolution of the temperature and velocity contours are also observed here except slightly higher maximum velocity values obtained from the wound woven wire matrix case.

Fig. 9 shows the relationship between Nusselt number and Reynolds number for the wound woven wire matrix simulations and the solid line presents the Nusselt number correlation line derived from the present results. It is found that the average Nusselt number coefficients obtained for wound woven wire matrix are significantly lower (20%) than those obtained from the stacked woven case for a range of $20 < Re < 400$.

For wound woven wire matrix configuration the three coefficient correlation that better fits with the numerical results is shown in the Eq. (20), where the Reynolds number is calculated based on the hydraulic diameter:

$$Nu = 1.54 + 0.29Re^{0.66} \quad (20)$$

The above numerically derived Nusselt correlation equation could be considered to be a good general approximation to be applied to all configurations studied here for the wound woven wire mesh matrix. In addition it should be noted here that the dispersion at high Reynolds number (Maximum standard deviation of 4.4) for the wound woven wire mesh matrix is higher than that for the stacked woven wire mesh (Maximum standard deviation of 1.4). Therefore, it is suggested that the geometrical parameters should be studied carefully in this configuration.

Fig. 9 shows the Nusselt number results for different volumetric porosities, specific heat transfer areas and hydraulic diameters in a range of Reynolds number. As expected, the higher Nusselt numbers are obtained for the matrix configuration with higher specific heat transfer area (Eq. (7)). Regarding the influence of the hydraulic diameter, the results show an inverse proportionality with the Nusselt number, in other words, the Nusselt numbers increase when the hydraulic diameter decreases. Finally, the results tendency in function of the volumetric porosity is not evident for the matrix configurations studies (see Table 3); therefore, no clear influence of the volumetric porosity in the Nusselt number can be concluded. Thus, no relation between increase/decrease volumetric porosity and the Nusselt number increase/decrease was observed.

The matrix geometrical parameters, hydraulic diameter (Eq. (12)) and specific heat transfer area (Eq. (13)), are function of wire

diameter and volumetric porosity. Consequently, an decrease the volumetric porosity causes a decrease in the hydraulic diameter and an increase in the specific heat transfer area for the same wire mesh. Accordingly, the interaction between the matrix geometrical parameters, specific heat transfer area, hydraulic diameter and volumetric porosity require an in-depth study to isolate the influence of each one (see Table 2).

4. Conclusions

In the present numerical study, a specific correlation is derived to numerically characterize heat transfer for wound woven wire regenerator matrices following by an initial numerical validation against experimentally obtained correlation for stacked woven wire.

The validation results show that the derived correlation can be successfully applied in the Re number working range in Stirling engine regenerators ($4 < Re < 400$), for diameter range from 0.08 to 0.11 mm and a volumetric porosity range from 0.60 to 0.68. The numerical study, which is extended to wound wire model case, also demonstrates an easy and effective use of the derived correlation for determining the Nusselt number for the wound woven wire model for a large Reynolds number range up to 400. The behavior reported in the present study for stacked and wound woven wire matrices are for “random or misaligned stacking” in contrast to “regular or aligned stacking”. It is believed that this new correlation can be also used as a generalized cost-effective tool for heat transfer characterization and further optimization in wound woven wire matrix type of regenerator.

In the Stirling engine calculation program are needed correlations to determine the heat transfer and flow friction behaviour of the working gas in the different components, for this reason is fundamental the characterization of the main components as heat exchangers and regenerators. The results shown here demonstrate that the present numerical tool can be used to study the influence or effect of matrix geometrical parameters (volumetric porosity, hydraulic diameter, specific heat transfer area, etc.) to improve the woven wire matrix heat transfer mechanism. Therefore, further efforts are necessary, in order to derive more experimental data which may support the new correlations.

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